

Variability in the Lambda Orionis cluster substellar domain^{*}

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Abstract. We present the first results on variability of very low mass stars and brown dwarfs belonging to the ~ 5 Myr Lambda Orionis cluster (Collinder 69). We have monitored almost continuously in the J filter a small area of the cluster which includes 12 possible members of the cluster during one night. Some members have turned to be short-term variable. One of them, L Ori 167, has a mass close to the planetary mass limit and its variability might be due to instabilities produced by the deuterium burning, although other mechanism cannot be ruled out.

Key words: stars: low-mass, brown dwarfs – stars: variables – Galaxy: open clusters and associations: individual: Collinder 69, Lambda Orionis

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1. Introduction

We are embarked in a very ambitious project devoted to the Lambda Orionis Star Forming Region (SFR), the Head of the Orion giant, the Hellenic mythological hero. This area contains several distinct structures, including several dark clouds with active star formation and a very young cluster (Collinder 69 or Lambda Orionis cluster) associated to the multiple star λ Ori, located at the center of the SFR. Additional details can be found in Dolan & Mathieu (1999, 2001) and Barrado y Navascués et al. (2004, 2005). This paper deals with a specific topic: variability at the bottom of the stellar sequence in the Lambda Orionis cluster. Specifically, we are interested on the faintest object in our sample, trying to establish whether the variability arises from pulsation due to deuterium burning, a mechanism initially proposed Toma (1972) –based on previous work by by Gabriel (1964)– for pre-main sequence stars ($2.0\text{--}0.2 M_{\odot}$) and recently suggested by Palla & Baraffe (2005) for young brown dwarfs.

So far, few young brown dwarfs have been photometrically monitored, and their periods derived (see Scholz et al. 2005, this volume). The pioneering work dealt with a handful of very low mass members of the Pleiades cluster (Terndrup et al. 1999; see also Scholz & Eislöffel 2004a). The youngest objects belong to Chamaeleon I (1–3 Myr),

and they have the longest periods, in the range of 53–114 h and with amplitudes in the J band of 0.13–0.05 mag (Jørgensen et al. 2003). Several works have focused on brown dwarfs of the somewhat older (3–5 Myr) σ Orionis cluster (Bailer-Jones & Mundt 2001; Caballero et al. 2004; Scholz & Eislöffel 2004b). They have unveiled periods in the range 3–240 h, with amplitudes of 0.02–0.4 mag. However, the lowest mass object whose variability has been detected so far, S Ori 45, has a mass about $0.02 M_{\odot}$. Its period has been estimated as 0.50 ± 0.12 h (Bailer-Jones & Mundt 2001). Later on, Zapatero-Osorio et al. (2003) derived two possible periods, either ~ 0.77 h or a value in the range 2.5–3.6 h, with amplitudes in the range 0.01–0.13 mag. Because of escape velocity arguments, the shortest period cannot be the rotational period. Palla & Baraffe (2005) suggested the possibility of pulsations due to deuterium burning. However, except for S Ori 45, and taken into account the age, the other objects seem to be too massive (larger than $0.05 M_{\odot}$) to be undergoing deuterium burning (ie., they should lack pulsations driven by its combustion). We will discuss the observations and data analysis in the next sections.

2. Analysis

2.1. The observations

The data presented in this paper were collected during two campaigns in November 19–20 2002 and February 12–14

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^{*} Observations collected at the WHT, Roque de los Muchachos Observatory, Spain

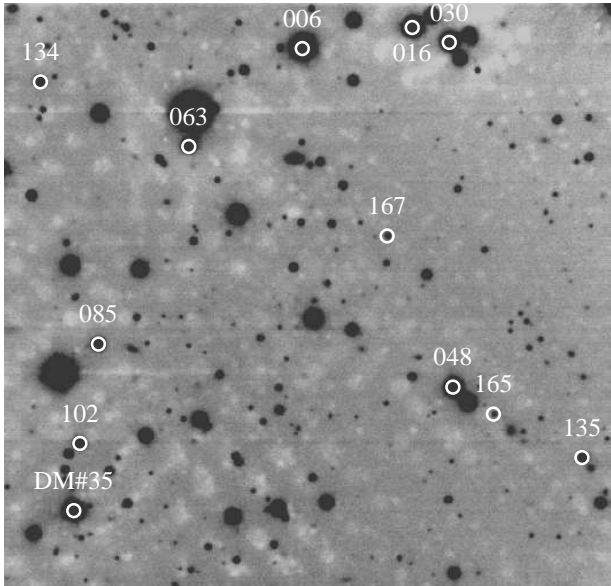


Fig. 1. Deep INGRID image in the J band of the area south-east of the star λ Orionis. We have marked the cluster candidates from Dolan & Mathieu (1999) and Barrado y Navascués et al. (2004).

2003 at the 4.2m WHT, La Palma (Spain), and the near infrared camera INGRID, which has a 4.2×4.2 arcmin² field of view. During the first run, we divided the area around the Lambda Ori cluster in a 42×28 arcmin² grid, composed of squares of 4×4 arcmin each, trying to match our CFHT optical survey (Barrado y Navascués et al. 2004). We used the J filter, but in few cases we took additional data with the filters H and Ks . The exposure times were five individual exposures (with a small offset) for each pointing of 60 seconds each. Therefore, the total exposure time was five minutes per pointing. The same procedure was repeated during the 2003 run. These observations will be reported elsewhere. The data were processed using IRAF¹.

Here, we analyze the data taken just southeast of the λ Orionis star. In 2002 we collected $JHKs$ imaging of this pointing, whereas in 2003 we devoted a whole night, with a five-hour time-span, in order to observe this small area in the J band, looking for short term variability. The individual 60 seconds exposures were processed, aligned and combined into one single 5 minutes frame. In total, we collected 51 of such five-minute images. In addition, we combined all the frames into a single image in order to derive deep, accurate photometry. The final deep image can be seen in Figure 1, where we have marked the location of our targets. The star BD +09 879C, the third component of the λ Ori system (30 arcsec south of the primary), can be partially seen at the upper-right corner of the finding chart. Optical and near infrared photometry, as well as a mass estimate based on a 5 Myr isochrones by Baraffe et al. (1998) are listed in Table 1.

¹ IRAF is distributed by National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract to the National Science Foundation, USA

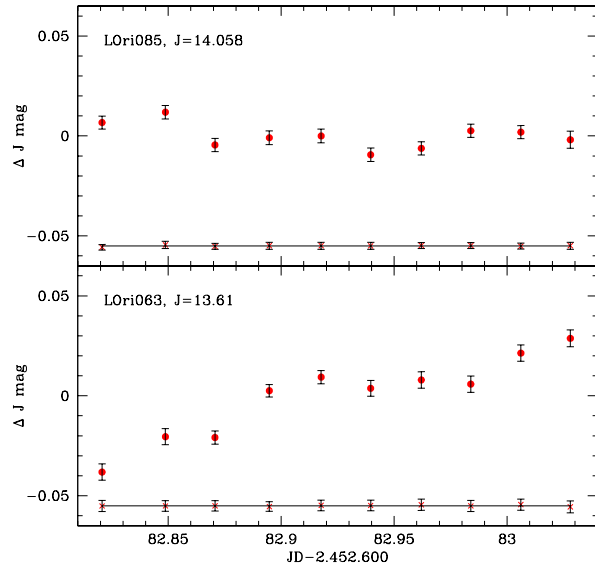


Fig. 2. Light-curves for two low mass stars belonging to the Lambda Orionis cluster. These objects have been classified as Classical T Tauri stars based on their location on infrared color-color diagrams, using Spitzer data. The data for the comparison stars are shown at the bottom of each panel.

Note that we have previously collected low resolution spectroscopy for two of the objects listed in Table 1, LOri 134 and 135. The spectral types are M5 and M7, and they were classified as probable non-member and possible member, respectively, based on their spectral type and the optical and 2MASS photometry (less accurate than our new values). Based on the new photometry (including Spitzer/IRAC data, see Barrado y Navascués et al. 2006, in preparation), we have classified them as cluster members. The other objects analyzed here, except for LOri165, seem to be members of the association too.

2.2. Analysis of the variability

The J -band light-curves of the bona-fide members are displayed in Figures 2–4. The first diagram displays the curves for two low mass stars, whereas the second shows the data for two probable brown dwarfs. The last figure (Figure 4) corresponds to an object with a mass around the planetary mass limit ($\sim 14 M_{\text{Jup}}$). These light-curves have been constructed subtracting the magnitudes of the targets from a non-variable, artificial comparison star.

In order to construct the artificial comparison or reference star we have analyzed the light-curves of field stars with magnitudes as similar as possible to those of the targets. From these objects, we have selected those that do not display significant variability over the five hours of observations. The reference star is built by selecting field stars in a range of ± 2 mag around the problem star. After several iterations to remove variables in the field, we retain between 5 and 7 stars with no apparent variability. On average, the standard deviation of their brightness is below 0.008 magnitudes. We have

Table 1. Photometry of our candidate members.

Name	R_c error	I_c error	J^1 error	J^2 error	H^2 error	Ks^2 error	Mass ⁶ (M_\odot)	Sp.T.	Var?
[DM99] 35 ³	14.48 0.01	13.61 0.01	12.136 0.001	12.26 0.01	11.60 0.01	11.55 0.01	0.785 0.739 0.571		
L Ori006	13.55 0.01	12.75 0.01	11.430 0.001	11.67 0.01	10.90 0.01	10.94 0.01	1.106 1.171 0.901		
L Ori016	14.07 0.01	13.18 0.01	11.902 0.001	12.00 0.01	11.41 0.01	11.27 0.01	0.970 0.875 0.696		
L Ori030	14.95 0.01	13.74 0.01	12.314 0.001	12.44 0.01	11.81 0.01	11.64 0.01	0.735 0.655 0.537		
L Ori048	15.78 0.01	14.41 0.01	12.622 0.002	12.78 0.01	12.17 0.01	12.00 0.01	0.498 0.534 0.418		
L Ori063 ⁴	16.80 0.01	15.34 0.01	13.610 0.002	13.72 0.01	13.02 0.01	12.69 0.01	0.287 0.269 0.261	M4.5	Y
L Ori085 ⁴	17.65 0.01	16.04 0.01	14.058 0.003	14.21 0.01	13.58 0.01	13.26 0.01	0.184 0.194 0.170		N
L Ori102	18.24 0.01	16.50 0.01	14.430 0.004	14.57 0.01	14.05 0.01	13.78 0.01	0.137 0.147 0.113		
L Ori134	19.91 0.01	17.90 0.01	15.609 0.006	15.72 0.01	15.17 0.01	14.82 0.01	0.063 0.059 0.046	M5	Y
L Ori135	19.91 0.01	17.90 0.01	15.529 0.006	15.63 0.01	15.14 0.01	14.79 0.01	0.063 0.063 0.048	M7	Y
L Ori165 ⁵	23.12 0.22	20.73 0.02	18.497 0.026	18.57 0.05	18.08 0.05	17.83 0.09	—		
L Ori167	23.86 0.64	20.90 0.02	17.776 0.017	17.84 0.03	17.15 0.03	16.62 0.03	0.018 0.014 0.015		Y

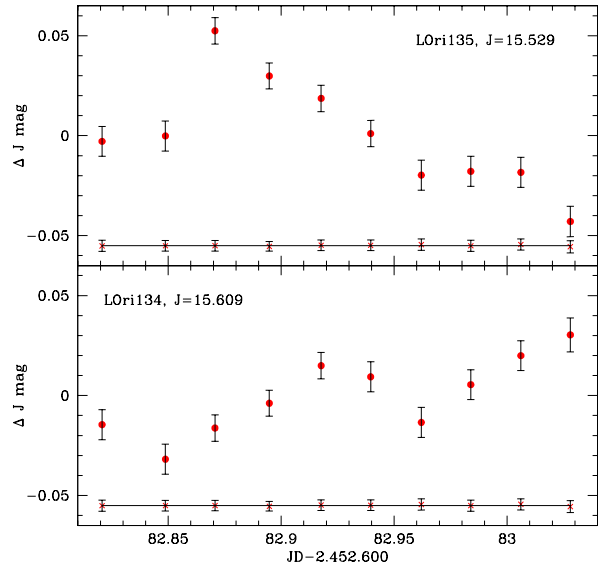
¹ INGRID Feb. 12, 2003.² INGRID Nov. 19, 2002.³ From Dolan & Mathieu (1999), the spectral type is in the range K8–M2, from the colors.⁴ Class II object, based on Spitzer/IRAC data (Barrado y Navascués et al. 2006).⁵ Possible non-member.⁶ As derived from I , J and K magnitudes, $(m - M)_0 = 8.010$, $E(B - V) = 0.12$ mag and 5 Myr isochrones from the Lyon group.

weighted them according to their observational errors and computed their average magnitude. We have used a 3σ as our variability criterion. In all figures, the light-curves of the comparison stars together with their mean J -band magnitudes are shown below the light-curves of the targets.

2.3. Variability on the context of the evolutionary status

Figure 5 displays the HR diagram for our targets. Bolometric luminosities were derived after the I magnitudes the bolometric corrections by Comerón et al. (2000), a distance modulus of 8.010 mag and $A_I = 0.223$. Similar values can be derived from J and K using other bolometric corrections. Effective temperatures come from Bessell et al. (1991) and the $(R - I)$ color. Note that the T_{eff} scale change very much the Pre-main-sequence locus. For instance, the scale by Leggett (1992) would move the cluster sequence close to the 1 Myr isochrone. Moreover, error-bars for a given temperature scale can be close to 150–200 K. For the dataset represented in the diagram, the 5 Myr Baraffe et al. (1998) fits the location within the errors. The figure also includes the D-instability strip (delimited by thick, dashed lines), which appears due to deuterium burning during the first million years of pre(sub)stellar evolution.

L Ori085 and L Ori063 can be classified Class II objects based on Spitzer/IRAC data (Barrado y Navascués et al. 2006). For the first star, it seems that the variability, if present, is very small, at the same level as in the case of the comparison star (in our dataset, $\sigma_{\text{L Ori085}} = 0.007$ mag, whereas $\sigma_{\text{comp}} = 0.004$ mag). However, there is an obvious change in the case of L Ori063. Its variability can be due either to spots or changes in the accretion rate. In the first cases the variability would be essentially periodic (with a range from few to hundred of hours), whereas in the second case the light-curve would lack periodicity. Our dataset do not allow us to distinguish between these possibilities.

**Fig. 3.** Light-curves for two brown dwarf candidates.

L Ori134 and L Ori135 seem to be bona-fide brown dwarfs based on photometry and their spectral type. Based on Spitzer/IRAC data, they can be classified as Class II and Class III objects, respectively, although L Ori135 might have IR excess at 3.6 and 4.5 micron. At the timescale of our photometric monitoring, the light-curves seem to be very different.

L Ori167 is a cluster member based on its optical and near IR data and its spectral energy distribution (from the R band to 8.0 micron, Barrado y Navascués et al. 2006). It is located close or within the deuterium string instability in a HR diagram (Figure 5). The question is: Are we detecting pulsation? The light-curve suggests a period of about one hour. However, error-bars are large and the time coverage is not optimal to confirm this suggestive possibility.

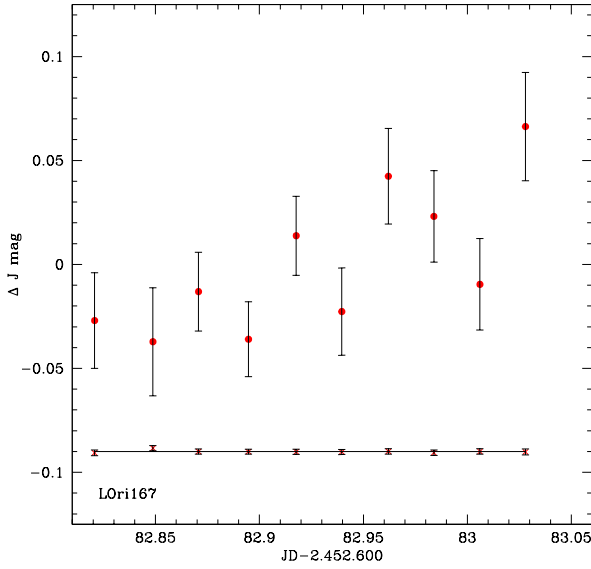


Fig. 4. Light-curve for LOr167. If member, this object would have a mass slightly above the the deuterium burning limit, located at $0.013 M_{\odot}$. Due to the cluster age, pulsations might be present.

Note that the theoretical prediction by Palla & Baraffe (2005) gives a period $P(\text{D-instability}) \sim 1.5$ h. Moreover, for an age of 5 Myr, the radius of LOr167 would be $0.225\text{--}0.143 R_{\odot}$ for a $0.02 M_{\odot}$ brown dwarf (NextGen or COND models by the Lyon group). The escape velocity for this object would be 173 or 231 Km/s for each model, after applying the formulae $V_{\text{escape}} = 617.88 \times [M(M_{\odot})/R(R_{\odot})]^{0.5}$. Therefore, the minimum rotational period would be $P_{\text{rot,min}} = 2\pi R/V_{\text{escape}}$, which translates into 1.79 h or 0.75 h for for NextGen and COND models, respectively. Since for the mass and T_{eff} of LOr167, the COND models are better suited to describe its properties, and due to its location in the HR diagram (very close or within the D-instability strip), it seems that it is a real possibility that we have discovered a D-burning pulsation. In any case, as stated before, this is just a possibility, and other explanations, more conventional, are still possible (such as variability due to spots or clouds in the atmosphere of the object). Additional data, covering several nights and with better photometric accuracy, are needed.

3. Conclusions

By photometrically monitoring in the J band a sample of low mass members of the Lambda Orionis cluster, both stars and substellar objects, and using differential photometry, we have derived the light-curves in a five-hour time-span. We have detected variability in some of them, including a Classical TTauri star, two brown dwarfs and a very faint object with $J=17.8$ mag, which corresponds to a mass close to the planetary mass domain for cluster members. This variability, with an amplitude of about 0.1 mag, might be due either to rotation, accretion or to instabilities –i.e., pulsation– due to the

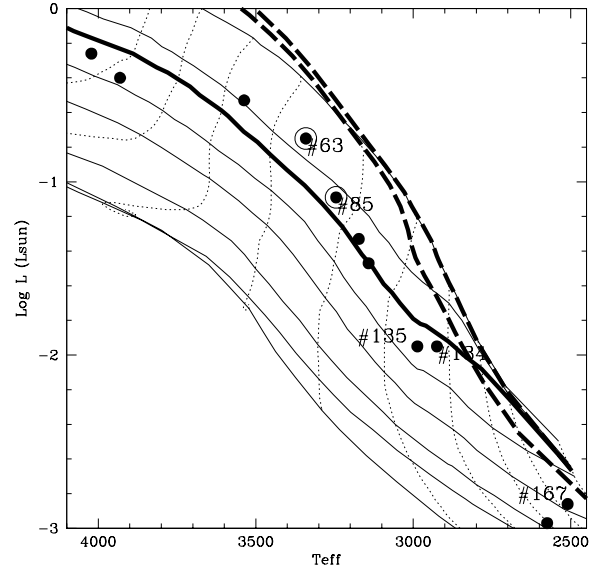


Fig. 5. HR diagram for our cluster candidates. We have included isochrones (from top to bottom 1, 3, 5, 10, 20, 50, 100 and 1000 Myr, solid lines) and evolutionary tracks (from left to right 0.02, 0.03, 0.04, 0.06, 0.1, 0.2, 0.4, 0.6, 0.8, 1.0 M_{\odot} , dotted lines) from Baraffe et al. (1998). The 5 Myr isochrone has been highlighted. The area delimited by the two thick dashed lines correspond to the deuterium instability, where pulsation might occur.

deuterium burning, as proposed by Palla & Baraffe (2005) for very low mass objects.

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